Properties of Metals at Extreme Loading Rates

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Traditional thermodynamics tells us that all systems exhibit a tendency to maximize entropy. So it is a struggle to understand why so many thermodynamically open systems are able to survive with their organizational and functional integrity intact. Progogine, who won the Nobel Prize in Chemistry in 1977, concluded that the secret to survivability is in an exchange of energy. A stable complex system receives low-entropy energy from the environment while giving away energy that is entropy rich. A sustained exchange of the energies is in fact the condition for survivability. Since these phenomena are rarely observed in solids, mean-field theories of nonlinear continuum dynamics often provide sufficient representation of the solid behavior. These theories describe the deformation and damage processes with the use of constitutive models. In addition, an equation of state (EOS) that couples high hydrostatic pressure with changes in mass density and temperature is formulated. Difficulties arise when a metal is subjected to extreme loading rates and becomes a thermodynamically open system characterized by an exchange of energy caused by dislocations traveling long distances with a nearly sonic velocity.

Our dynamic defect structure (DDS) model described in [1, 2] predicts that various metals (alloys) subjected to extreme loading rates experience a strong mesoscale excitation leading to an entrapment of kinetic energy. While a significant portion of the energy is converted into heat, the remaining part supports a rearrangement of the material's internal structure and causes fluctuations in the field of velocity, strains, and stresses. The DDS model explains the remarkable increase in the plastic hardening rate [3, 4] observed in copper, iron, and nickel at strain rates greater than 10^3 s^{-1}. Also, the model suggests that at these conditions a heterogeneous phase transformation and melting are possible. In our numerical simulations, we were able to reproduce conditions at which two copper plates shown in Fig. 1, when impacted with each other, experience a noticeable excitation.

Our objective is to identify a dilatational deformation in ductile metals, which may impede the formation of the DDS structures. The material's dilatancy is allowed to exist. However, instead of imposing a predetermined relation for void nucleation a different approach is pursued here. We assumed [5] that the rate of void nucleation together

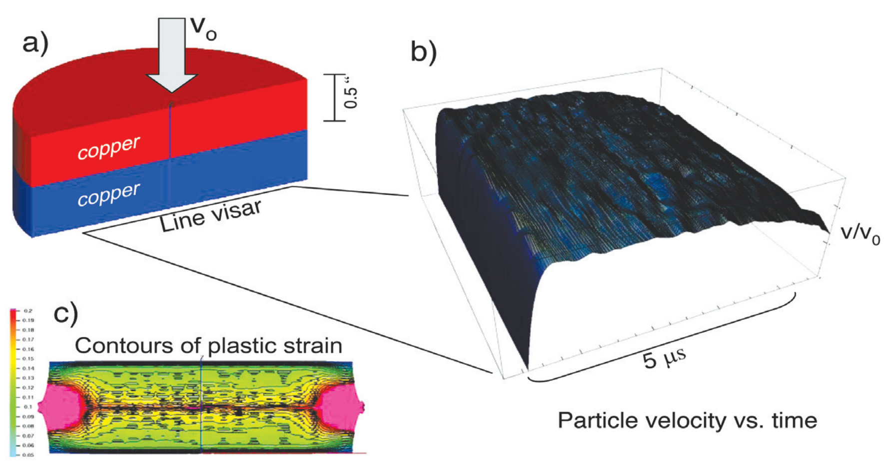

Fig. 1. ***Dynamic behavior of a copper plate subjected to impact loading: a) Cu/Cu plate impact; b) particle velocity as a function of time; and c) contours of plastic strain.***

with the rate of dissipation due to volumetric change and shear are nonnegative quantities at any point of the material. The missing constitutive equation for void nucleation is replaced by a criterion of minimum rate of energy dissipation. In this manner, the volumetric deformation brings the material as close to its thermodynamic equilibrium as possible. As shown in Fig. 2, three distinct mechanisms of void nucleation are possible near the ductile surroundings of the mode I crack tip. In this plot, values of the minimum energy triaxiality ratio X (vertical axis) are plotted as a function of the stress singularity factor λ (horizontal axis); where the stresses near the crack $\sigma_{ij} = R^{\lambda}\hat{\sigma}_{ij}(\theta)$ are defined in the polar coordinate system $\{R, \theta\}$ attached to the crack tip. The first mechanism (red line) describes the well-known Gurson's (stress triaxiality, σ_{kk}/σ_{eq}) criterion, where voids are uniformly distributed near the crack tip. At a more advanced stage of deformation (brown line) voids nucleate predominantly along a narrow process zone extending ahead of the crack. This mechanism is governed by the maximum tensile stress. There is also a third cavitation mechanism (blue line), in which voids are distributed along two branches at 50 degrees with respect to the crack direction.

Our findings are twofold: 1) Some metals, when subjected to extreme loading rates, exhibit the behavior that is characteristic of a thermodynamically open system. This phenomenon is linked to the high mobility of dislocations that travel long-distances and exchange energy and information between distant material points. 2) It is possible to bring the material close to its thermodynamics equilibrium at the length scale at which the mesoscale dynamic excitation occurs. The first analysis suggests that the void nucleation is such a mechanism. If voids do not nucleate, then the development of the orderly dislocation structures is the most favorable mechanism.

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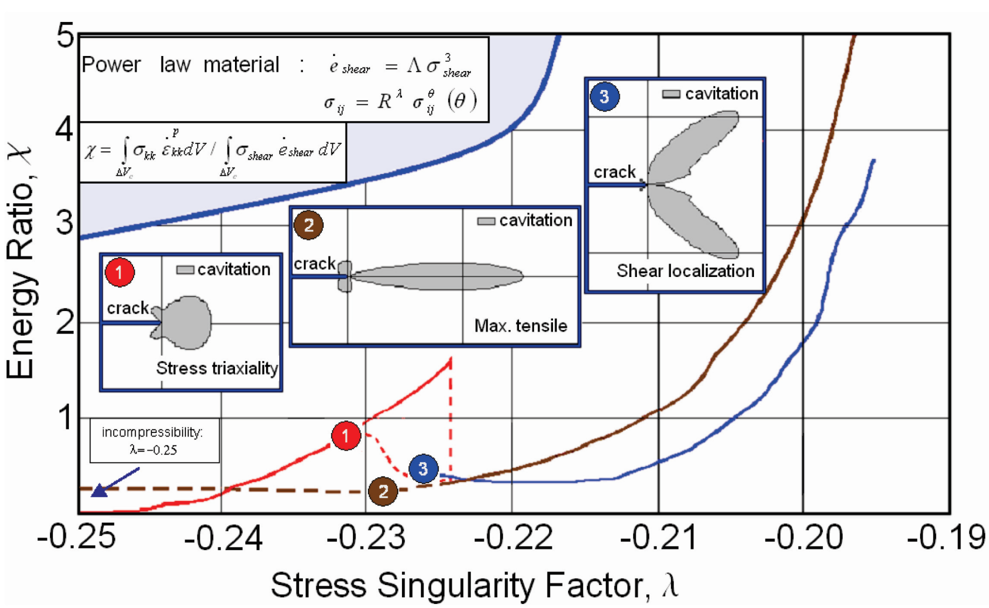

Fig. 2.
Three mechanisms of void nucleation in ductile surroundings of mode I crack tip.